National Defence / Défense nationale

COMPUTER-AIDED DESIGN AND BIO-ENGINEERING: A REVIEW OF THE LITERATURE (U)

by

D. Hidson
Chemical Protection Section
Protective Sciences Division

DEFENCE RESEARCH ESTABLISHMENT OTTAWA
TECHNICAL NOTE 88-31

July 1988
Ottawa

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ABSTRACT

This paper contains a review of the expanding use of computers and computer-aided design in the fields of bio-engineering, human engineering, medicine and anthropometry. Work done in recent years on modelling complex biological shapes and some methods of shape analysis are assessed. A bibliography is included.

RÉSUMÉ

Cette note technique contient une revue de l'expansion dans l'utilisation des ordinateurs et de la conception assistée par ordinateur dans les domaines de la bio-ingénierie, de l'ingénierie humaine, de la médecine et de l'anthropométrie. On évalue aussi le travail accompli au cours des récentes années dans le but de modéliser les formes biologiques complexes de même que quelques méthodes d'analyse des formes. Une bibliographie est incluse.

TABLE OF CONTENTS

1.0 INTRODUCTION

Today, almost every branch of engineering uses computers in one form or another and medical science, anthropometry and bioengineering are no exception.

The use of computers has come relatively late to these disciplines as large amounts of computing power and sophisticated graphics are required for the complex data generated by the human body. If one is using computers to generate a graphical representation of the human body (as in anthropometric studies) or to determine the shape of the cockpit of a fighter aircraft, large quantities of data must be handled, as rarely are these variables expressable as simple geometric functions. One of the reasons for the delay of computer applications has been the lack of the capabilities of computer graphics to render these data in a useable and visible form. The recent advances in image generation and processing, in terms of complexity and speed, have enabled workers in these fields to adopt computers for tasks which would have seemed impossible only a few years ago.

This paper contains a short review of some of the applications of computers in bio-engineering and the use of computer-aided design in anthropometrics, bio-engineering and medical science. Canada. (KT)

2.0 LITERATURE REVIEW

2.1 EARLY BIOENGINEERING ATTEMPTS

One of the earlier attempts to process human factor quantities by means of computers and to use this computerized process as a design aid was reported in "Combiman - Computerized Bio-mechanical Man-Model" by K.H. Kroemer (1). Combiman was an effort to model the size, shape, mass properties and joint movements of a human form graphically, using computer graphics. The idea was to produce a computerized, anthropometric, biomechanical and ergonomic model of the human form.

To construct this model, the problem was approached in three, distinct conceptual phases: anthropometric, biomechanical and ergonometric. The first phase, the "Anthropometric analog", was designed to ensure that the model contained the standard anthropometric data of the subjects, that data was stored on subjects wearing special equipment, and that calculations on changes in anthropometric descriptors (produced by variations in posture, etc.) could be done. The second phase, the "biomechanical analog", was designed to represent body mechanics by modelling the linkage system and mass properties of the human body. The combination of these two phases generated the third phase, the "ergonomic phase". This was to combine the physical characteristics of the human body and the physics of the workplace in such a way as to assess interactions between variables and indicate that certain physically-defined task requirements can be met within the given constraints.

The first models (before Combiman) were of the various "stickman" type: straight line connections of two- and three-dimensional joints, but in 1964, Hanavan developed a model of the human body with inertial properties which was, in itself, a major advance. The Combiman model was to be a further advance.

The first phase of development was to allow complete storage of anthropometric information. The modelling done using this information was to manipulate the stored data to take into account actual changes representative of real working situations. The second phase would incorporate dynamic properties, that is, the model would react to external forces such as g-fields and vibration. The "active" version would incorporate internal forces, torques, work and power capabilities. The third phase of the model included models of the workplace with which the Combiman model interacted.

In the late 1960's and early 1970's, several attempts were made to model the human form. Because computer graphics in those days was an infant technology, most of the computer models relied heavily on certain algorithms to compute the position and motion of the modelled form with a very limited CRT display. Some models (Bulgar (1967) developed by Popodimitrov (2), Dynastick (1970) developed by Wartluft (3), Torque Man (1968) developed by Chaffin (4) and MTM Man (1970) developed by Kirpatrick (5)) contained only information on the body's links and joints. Only the shape and strength of various joints were included as other variables. Torque Man was only a two-dimensional model. Some other models, Boeman (developed by Boeing Aircraft Company in 1971) (6) contained some mechanical or ergonometric variables. Dynastick, although a stick model, did contain some mass properties as determined by Clauser, McConville and Young (1969).

These models did not all perform the same task but provided a variety of outputs depending on the input. For example, the Boeing "Boeman" model required anthropometric data, cockpit descriptors and a defined path of the hand as input and would output the joint angles and a

pass/fail decision as to whether or not certain controls could be reached. Most of these models were programs that output certain data and did not consist of an array of impressive graphics.

As the Combiman model was going to be a dynamic model, the mathematical structure of it had to be formulated to allow efficient computer handling. Apart from performing calculations, the model had to store large amounts of anthropometric data for static configuration displays and to be able to handle complex algorithms describing the various motions and linkages of the limbs and torso. Further, the model had to be useful while still incomplete, in other words the algorithms would have to have the capability of being amplified and expanded while remaining functional.

This was an ambitious project, and four years later, in 1976, it was still not complete. It was reported by F.J. Bates et al. (7) that, at that time, the model structure consisted of 33 links, 19 flexible joints, 6 fixed parts and 9 peripheral parts. The model structure, the number of joints and links and their arrangement could be changed easily. In this work, the authors developed a programmable, mathematical version of the Combiman model. The hip joint was taken as the base point of the linkages and from this base point a chain of links could be traced to any peripheral point.

Several ways of describing the man-model were examined, beginning with the simple specification of joint locations. For a realistic man-model, the angular limitations of the flexible joints had to be represented. This was done by using the Euler angles that are commonly used in rigid body dynamics. These angles define the three rotations with respect to the coordinate axes. Since the links were all known quantities, a matrix equation could be set up representing the transformations at the pivot points. With a knowledge of the approximate maximum, minimum and optimum values of the Euler angles for specific human joints, the solution of a variety of matrix equations will allow the configuration of the Combiman model to be deduced in normal three-dimensional space. During the execution of a task, the paths of peripheral points and extremities of the body were known, so the major computing problem was to find the values and distribution of the Euler angles of the other joints and so to generate the configuration of the model. A couple of different techniques were used for this such as multi-dimensional optimization techniques but suffice it to say here that the Combiman project was one of the first to address the problem of human body motions being represented in a computer image. The image here is, of course, a mathematical image and not a sophisticated graphics display.

2.2 CRASH SIMULATION

The need for knowledge of how the human body behaves in traumatic situations like automobile accidents is readily apparent. This, too, has been the subject of computer modelling techniques for obvious reasons.

When mathematical modelling is used, its effectiveness is always open to question. This very problem was examined in some detail by G. Frisch and J. O'Rourke (8). Their paper was entitled "The Effectiveness of Mathematical Models as a Human Analog". Here they considered three biomechanical modelling programs, "Three-D Computer Simulator of Motor Vehicle Crash Victims" (9,10) by Calspan Corporation; "Crash Victim Simulator - Light Aircraft" (11) and "Prometheus" by Boeing (12,13). This type of modelling program was developed by various companies as tests with human subjects were too dangerous and experiments with manikins very variable. At that time there had been very little success with modelling because of the complexities of the human body itself and the limitations of earlier computers.

A set of tests was designed and carried out on human subjects. These were tests designed to measure the response of the subject to -Gx accelerations i.e. stopping quickly. External anthropometric data was obtained for the body and X-ray data for the head. The X-ray data was necessary to allow the fixing of transducer mounts to well defined anatomical systems. All of these programs were variants of the Dynastick concept, that is, a linkage and pivot representation of the human body. These, however, contained information on mass, moments of inertia, link lengths and locations of various segments' center of gravity. Other attributes of the models were ball and socket joint representation (except for elbows and knees which were considered hinged). Head-neck and neck-torso movements were included in the head motion analysis; friction and viscous retarding forces were included in the joint descriptors.

When each of the programs was tested, a variety of variables was recorded including angular acceleration of the head, lap belt loads, head angular velocity and resultant linear acceleration.

The Calspan 3-D Computer Simulator contained a sixteen-segment, fifteen-joint representation of the man with the provision for usage of a sophisticated shoulder joint model with ball and socket connections and muscles simulated by spring dampers. As the simulations were run with the shoulder straps 'in place', the thorax could exhibit greater excursion than the shoulders themselves.

The CVSLA program (Crash Victim Simulator - Light Aircraft) consisted of a three-dimensional man-model, aircraft seat and restraint system. This was, of course, designed to investigate the crash worthiness of various seats and restraint systems for commercial aircraft. Here, rigid seats and soft seats could be simulated as well as forced elongation of shoulder strap webbing on an eleven-segment body. The segment properties were reduced to fractions of total body weight and stature. These fractions, along with other factors to account for body size, were used to calculate the subject's anthropometric characteristics. This program differed somewhat from the Calspan model in that the head and neck were treated as one mass unit.

The Prometheus program from Boeing was a two-dimensional crash victim simulator with an occupant consisting of seven links, lap and shoulder belts and an interaction with the environment through a non-linear finite-element model of the seat structure. As many variables as possible were made to match those in the Calspan program (for instance, head-neck center of gravity position). This was to enable the investigators to make as many comparisons as possible between the actual execution methods of the programs. This had to be done in order to ensure that differences in the results were not due to differences in the numerical integration procedures but to differences in the models themselves. The programs were run to ensure that they were virtually error-free but differences in the numerical integration packages cannot be totally ruled out as a source of differences in the results.

The various man-models consisted of a variety of joints and links and these were modified (for instance, the Calspan model had the head pivot and clavicular joints locked) so as to compare more directly with the Prometheus model.

The comparison of these models showed that results were fairly consistent but significant differences were apparent, for instance, in the predicted belt loads and the time that peak forces were attained. It was found that although the results of simulation programs agreed with one another quite well, their abilities to replicate test data were generally quite poor. Because all the programs were very sensitive to initial conditions, the lack of precise input parameters could lead to very different results due to only a small variation in these parameters. Despite the agreement of the program results, the comparison of these with the results of actual testing showed that the assessment of what were the relevant parameters from which to form a man-model needed some serious revision.

Some of the problems the authors encountered are readily understandable. Modelling a dynamic, biological system with a simple, mechanistic schematic will undoubtedly demonstrate differences and discrepancies. Bearing in mind the complexity of the human organism, it is perhaps remarkable that such a good agreement was observed.

2.3 MEDICAL APPLICATIONS OF COMPUTER MODELLING

As computer graphics has come of age, it has come to be a valuable tool in the medical world.

Modelling geometry itself, however, is easier as a large number of assumptions about dynamic properties of systems can be dispensed with. The geometric structures in biological forms that can be modelled vary in complexity from the icosahedral structure of viruses (14) to the shape of human bone structures. (Reference 14 will not be reviewed in detail.)

With the advent of computed tomography (CT) in the 1970's it became possible to perform three-dimensional reconstruction and visualization of the ventricular system and brain lesions (15). When CT is used on a patient, about twenty images are produced and these are all two-dimensionsal images. The authors here used computer software to generate a raster image. They used some technicues that utilized current two-dimensional CT head display systems. The computed surfaces were generated by taking the set of contour lines defined by the anatomical object and intersecting them with a set of parallel planes. The software then took these and generated a triangular mesh (similar to a finite-element mesh).

The actual contour lines were obtained from the tomography images in a variety of ways. A coordinate digitizer was used to select points on the two-dimensional curves generated from the CT scan. These points were then joined by a straight-line segments. Also, CT scans could be displayed on a graphics display and a screen cursor used to find the requisite points. The mesh was then generated and a perspective three-dimensional representation displayed.

From these displays, the medical staff involved obtained a clear picture of various internal parts of the body. Also, volumes could be estimated from the surface contours displayed. The major disadvantage of this system was that objects tended to become confused when more than three or four were displayed at the same time. This is still the case with most wire-frame displays today.

Visibility was greatly enhanced by surface shading. This gave the image the appearance of the "solid model" type of display and the depth-cueing reduced many of the ambiguities in perception. The "tiled" surface (constructed with the triangular mesh) was also color-coded to add to ease of perception and once the construction was complete, the anatomical objects could be viewed from any angle and position.

As was expected, as more features were displayed the surface tended to become confused and here color coding was very important. To make the surfaces more realistic, a shading algorithm was used on the surfaces. The intensity "painted" on each mesh triangle was linearly interpolated between the vertices to improve depth-cueing. The final improvement removed hidden surfaces from view.

As it was necessary to observe some of the hidden surfaces, they were rendered visible by diplaying the obscuring surfaces as transparent surfaces. This was done by displaying each element of the surface as a linear combination of the occluding surface intensity and the intensity of the surface behind it. This gave an excellent rendition of the surfaces.

There is considerable medical interest in knowing the volume of various organs in the body. Once the surface had been displayed, the volume problem could be tackled by means of a volume, or triple, integral over that region of three-dimensional space. If the object was regular, and possessed of a known geometric form, such as an ellipsoid, then the triple integral could be evaluated directly. If a simple and analytic form was not available, an iterative integration procedure was used to evaluate the volume.

The main purpose of all this modelling was pre-planning for complex brain surgery and radiation treatment for tumors. Obviously, in such operations, there is little room for exploration or error. Further, with radiation treatment, an accurate knowledge of the shape, size and position of the tumor would enable exposures of healthy tissues to be kept to a minimum. Repeated use of this technique allows the size and shape of a tumor to be monitored during and after treatment.

A similar use of computer graphics technology was described by M. Ameil and others in a paper on computerized reconstruction of anatomical structures (16). Here the authors reconstructed the ventricular part of an adult human heart by means of digitizing sections. A specimen heart was frozen and cut into sections one-half centimeter thick and each section was then photographed. The data was digitized and sections were made up. Displays were presented as wire-frame sections and as a solid, shaded model. The digitization and displays were performed with an Applicon CAD system. Each section contour had to contain the same number of points so that a mesh could later be built for the shaded surface. The surface was created by generating multiple quadrangular polygons. The shaded and smoothed surface was created from this but took large amounts of computer time - about seven hours in this case.

Apart from just static modelling, computer graphics are now being used to examine and analyze kinematic problems. In a paper entitled "Computer-Assisted Analysis of Ligament Constraints in the Knee" (17), Langrana and Bronfeld looked at modelling the shape and movements of some ligaments in the knee joint.

Most of the knowledge about the functions of these joint ligaments has come from two sources: studies of normal gait and examination of human cadavers. The location of the actual ligaments was found with the aid of computer-aided tomography (CAT) which gives radiographic density information. Most of the extraneous tissue was removed from a knee joint, care being taken to leave the ligaments uncut. Thin Kirschner wires were inserted into the surrounding tissue so that the attachment sites with respect to the bone could be recorded on the CT scan.

A jig fixed the specimen joint in the zero degree flexion position. Fixed wire frames were attached to the jig so that a radio-opaque grid would be generated and show up on the CT scans. This allowed the scan data to be digitized and the grid display allowed the scale to be fixed. Projector magnification errors were thus eliminated.

Two types of engineering analyses were performed. In one, the bone density profile at different scan slices was investigated and in the other, the geometry of the joint was reconstructed and the relative role of the four major ligaments was studied. The data enabled the knee joint to be modelled with three-dimensional computer graphics and allowed an analysis to be performed on how the loads in the ligament were shared.

A clinical stability test using a device known as KT1000 was used to assess this and the particular test was a passive draw test. This test was performed with the knee in the ninety-degree flexion position. A load was applied to the proximal end of the tibia (the top end of the lower legbone adjoining the kneecap) which pushes the tibia backwards. This was done again with the knee in the twenty-five-degree flexion position, and a load was applied to the proximal end of the tibia, this time in the forward direction. The KT1000 allowed both these tests to be performed with a standard load of eighty-nine newtons and a precise measurement of the relative bone motion was obtained. Sixty subjects were tested. The main data of the passive drawer tests were used in the simulated test to determine the load sharing in various ligaments of the knee. This was done by placing the computerized knee model at the proper flexion (ninety or twenty-five degrees) for that particular test; calculating the length of the ligaments in that position and then superimposing the passive draw data. The increase in length of the ligaments due to the test could then be calculated.

Several assumptions and approximations were made in the models of ligament tissue in respect of cross sectional area, elongation per unit force applied and the like. The bone densities of the CAT scan were converted into digital data and a three-dimensional computer model was created of the entire knee joint. Combined with the data of the passive drawer test the increase in ligament length due to the test could be calculated.

It was found that the pattern of elongation of the ligament fibers was in close agreement with that of the model. With certain assumptions about the nature of the physical properties of the tissues some fairly accurate predictions were made of their behaviour under stress using a computer model.

The possibility of using computer-aided design in dental and reconstructive surgery has been investigated by Arridge et al. in a paper entitled "Three-Dimensional Digitization of the Face and Skull" (18). These new surgical techniques have led to more complex and sophisticated modification of more parts of the facial skeleton. This surgery now includes the object of improving overall facial appearance rather than being limited to correcting purely physical functions. Indeed, the whole art of plastic surgery is devoted to just that. Most of the methods available now obtain only two-dimensional data from photographs, X-rays and CAT-scans. The standard technique here was to cut up profile photographs magnified to the same size as the standard lateral skull X-ray and to superimpose these over the hard tissue radiographs. These were then moved around to produce the best results.

Attempts to overcome the problems of acquiring accurate surface data have led to the development of stereophotogrammetry, laser scanning, sonic digitization and a variety of other techniques of shape assessment. Also, advances in computer graphics have enabled us to see solid modelling and surface shading brought to a point where extremely detailed and realistic images can be presented.

The approach used here consisted of a simulation of the old techniques. Computerized X-ray axial tomography was used. This type of scan was useful as it could distinguish beween hard and soft tissues. The three-dimensional aspect of the data was still generated by taking successive two-dimensional slices through the subject (about sixty-four parallel slices two millimeters apart) and constructing the three-dimensional image. An added disadvantage of this method was that it used ionizing radiation.

The experimental procedure used a CT scanning system and a television system driven by a single shared microprocessor. This enabled complete synchronization between patient and TV picture scan sequence. The data was extracted from the scene by means of two fanned laser beams projected vertically on to the face from an oblique angle and viewed from the front. This method avoided the "blind" spots, such as the sides of the nose, that are caused by extreme reflection angles from the subject surface.

The two data sets of facial and skeletal surfaces were stored in the computer as ordinary three-dimensional co-ordinates. To produce the image, the data points were joined up in such a way as to produced a triangular

mesh. This mesh was then surfaced and displayed as a shaded surface with hidden lines and hidden surfaces removed. This was in terms of computing time about two minutes on a Data General Nova. Part of the model (the skin and soft tissue part) was displayed as a semi-transparent surface so that the skeletal structure under it would be clearly apparent.

When this part of the procedure was completed, the data was in the form required, that is, the model could be cut up to simulate surgery. The biggest remaining problem was to gather data on the post operative effects of reconstructive surgery on the skeletal base and to see how this affected actual soft tissue regeneration. It was found during this work that the problems of getting a variety of computer systems to interface could be overcome.

2.4 COMPUTER-AIDED DESIGN AND BIOMECHANICAL ENGINEERING

Another very important part of the use of CAD/CAM in medical problems is the use of numerical control (N/C) machining for the production of things such as artificial joints in the area of biomechanical engineering. This has been described in some detail by S. Dore and J. Bobyn (19). In a paper entitled "Unique Orthopedic Implants" the authors described the use of computer-designed and manufactured artificial joints for patients suffering from various forms of arthritis.

In the past, various forms of treatment had been available for arthritic joints such as insertions of soft tissues between the articulating joints and/or replacement of one of the joints. This was the beginning of "mold arthroplasty" whereby the shape of a metal implant is matched to the geometry of a joint. The earlier forms of this treatment for arthritis involved making a copy of the bone geometry as closely as possible to the real thing and fixing this by means of a long stem inserted into the medullary canal (the bone marrow channel). The preferred type of treatment today involves the replacement of both articulating surfaces of the joint and this has been made possible by the development of several new techniques including PMMA - polymethyl methacrylate - a bone cement. This material acted as a grouting agent and filled the gaps between the prosthesis and the surrounding bone that allowed bone to grow around the implant and secure the prosthesis in place.

This process has worked relatively well in hip-joints, which, being ball-and-socket joints were inherently stable. However, for the knee joint, the stability was guaranteed by the surrounding muscles and not by

any intrinsically stable geometry. This was an added complication as PMMA had problems as a bonding agent. It was weak structurally and had some bad tissue reactions.

What was needed was an implant that had exactly conforming geometry to the shape under repair. This has been done for prostheses by taking an impression (in the case of amputee stumps) but for internal joints this was not possible.

So to circumvent this problem, CT (computerized tomography) was used to take eight scans perpendicular to the long axis of two femurs resulting in scans that were four millimeters apart. The result of this process produced a two-dimensional picture of the structure in a plane. This information was manually digitized to produce a three-dimensional set of data points. The data was then ready to be handled by an APT-based program called SSX7 which represented the surface as an ordered set of "m by n" points, about sixty in all.

The machining was performed on a five-axis milling machine. This avoided problems of repeated machining on a three-axis machine as in that case the work had to be repositioned on the table so that the cutting tool would not encounter conditions of undercut. Some surface gouging was reported and the final product, machined out of "NC wax" - a polyester material - was compared to the original by framing a negative of the replica with dental impression material and placing the negative on the bone. There was close agreement over most of the surface although errors of three millimeters were reported.

Errors were also generated by having a four-millimeter gap between each tomographic scan: newer devices have reduced this to one millimeter but the problem of excessive radiation doses to the patient may limit the viability of too many scans. The three-axis machining introduced errors because the work had to be rotated on the table to allow all the surface to be cut and be free of gouging.

Further work of a similar kind was reported by Walker, Rovick et al (20). Here the authors describe the analysis of knee motion and the construction of an average knee joint for prosthesis manufacture. An artificial knee joint was made up and mounted on a dynamic test rig in which the coordinate system was based on the femural geometry. A potentiometer on the axis measured the flexion angle of the knee joint and a load cell monitored force. Data was stored directly in data arrays in the computer. Two angles and three displacements of the femur relative to the tibia, as well as quadriceps force, were displayed graphically as a function flexion angle (knee bend).

The three-dimensional motion data was used in the design of external joints for a prefabricated leg brace. It was thought that if the external joints were constructed to mimic normal knee motion the brace

would move synchronously with the knee and when being used to provide support for an injured or post-operative knee, it would provide normal ligament length patterns.

The design was carried out using computer-aided design and a design optimization process was completed also. The optimization of the design would not have been possible without CAD as a complete analytical method would have been too cumbersome. By making small changes in the design of the brace and running the program, immediately changes and improvements were visible on the graphics display.

For some conditions replacement of the entire knee joint is necessary. Most designs for this use planar projection of the knee geometry but to attempt to get a better representation of the geometry a procedure was applied to determine an "average knee geometry" as a basis for joint design. The sections of twenty knees were obtained and superimposed on the computer screen where shape variations were immediately apparent. To generate an average shape, transverse lines were drawn across the peripheries around the profile of superimposed images such that these lines were perpendicular to the mean tangent of all profiles at that point. It was found that once the sections on the main joint bearing surfaces were normalized for size, the variations in shape were quite small being of the order of one millimeter.

A model of the knee was built up with the set of average profiles. The resultant surfaces in the model were modelled using analytical surfaces e.g. spherical surfaces and forms from other geometric solids rather than using a true sculptured surface generated from sets of spline curves. This process could be used on one particular knee as key dimensions could be taken by means of CAT scans or from radiographs and then fed into the surface generating program enabling individualized design to be performed.

After determining the form of the bearing surfaces, the femoral component was designed. The femur could be flexed on the tibia and in any regions where poor fit was detected, modifications to the surface could be made.

When designing the total knee joint, consideration had to be given to the face where metal and plastic parts would be working together. Design problems included degrees of freedom in the joint motions and how much should be allowed. Various tibial surfaces were designed by defining motion or stability criteria and constructing the tibial 3-D surface by moving the femoral component through a variety of positions so defined. A surface for average knee motion was generated by moving the femoral component through the flexion range. The surface coordinates were sorted in data arrays and a grid was defined in the horizontal plane and for each square on the grid the point with the maximum y-value represented a point on the tibial surface.

The graphics display was produced using a solids modelling package called Movie.BYU developed by H.N. Christiansen and colleagues at Brigham Young University, Utah (21). A Gould Deanza Image Processor was used in conjunction with a DEC minicomputer for the CPU. The Movie.BYU package displays solid models with simulated light sources and this combination requires a significant amount of computing power.

2.5 SHAPE ANALYSIS AND COMPUTER MODELLING

The most complex part of computer-aided design is usually the creation of CAD databases for complex shapes.

A recent advance in interface techniques was reported by Boulanger (22). For objects with regular shapes or geometric regularity the analytic design capabilities of the CAD system are generally used. But in the case of irregular shapes (such as human body forms) the data for such a shape has to be gathered by some scanning method on a point-to-point basis.

A system was developed at the National Research Council of Canada consisting of a line scanning laser and light sensor. The system can scan in a raster mode generating data in the form of an array of points or it can be used to make range measurements at randomly selected points. The device also allows the scanning of an object 360 degrees around a cylindrical axis.

The system consists of a laser light source, a scanning mechanism and an off-axis detector. The projection and detection of the light spot and its detection had to be done by a synchronized system so a pyramidal mirror was constructed for this. The distance from the projector to the object's surface was calculated simply by means of triangulation given the known orientations of the projector and detector. The detector is a lateral effect photodiode deposited on a sensitive layer. Because of the structure of this camera it was possible to obtain reflectance data from the object and 3D range data. The resolution available in the x- and y-dimensions was 1 mm and in the Z-dimension 0.5 mm.

The disadvantage with the raster scan process (any raster scan process) was that the whole field of view had to be digitized before any depth information on specific data points could be extracted. To overcome that problem, the authors designed a new model of camera that dispensed with the pyramidal mirror and used a plane mirror. The scanning minors were very precisely controllable. A cylindrical scanner, based on the same

technique as the random access scanner, was developed and this enabled an object to be placed on a rotating table and scanned up and down along the axial dimension so that complete 360° cylindrical data could be obtained.

To render multiple views of an object, the data obtained from different positions had to be merged. For irregular objects and a camera which is not a point this can be quite difficult as the location of a reliable origin is important. For a cylindrical scan, the merging of data was fairly straightforward. A scan was performed and the object rotated through a known angle and scanned again. The coordinate system was located by the axis of the cylinder and the merging of all the views was done by a fairly simple mathematical calculation on all the data. (Co-ordinate rotations on all the data sets). This enabled the data to be collected with no overlap between the data-sets.

Large quantities of data were generated; too much for surface rendering by means of regular graphics. The data set was pared down to a 256 x 256 array of range data points. Even this size of object or model was very large and could not adequately be displayed by a wire-frame image. So to overcome this difficulty the data was sampled every i-th point and presented as an array of 20 x 20 or 40 x 40 points. Sometimes it was required that data points be added for some of the spline curves in the geometry to be completed. In a B-spline representation of the data, the points become the nodes of the curves. The final form of the data presented a surface rendering and it was also in a form that could be modified for a CAD/CAM machining package such as POLYHEDRAL NC.

2.6 COMPUTER MODELLING OF ANTHROPOMETRIC DATA

Despite the fact that complex surfaces can be scanned by various techniques and modelled on a computer, several important problems remain with anthropometric modelling techniques.

Anthropometry usually deals with large quantities of point-to-point data taken from a human population sample representative of the nation or the larger population that the sample was taken from e.g. the military forces of the nation. If the data was to serve as the design basis for clothing, such as uniforms, or protective equipment, such as gas masks or helmets, then as these will only be made in a small number of sizes, some form of data averaging must be carried out. For instance, to produce a design basis for a gas mask or helmet, one would take various critical head and face dimensions in the survey and average them. Statistical data would

is available and some dimensions could be made one or two standard deviations larger or smaller than the average according as to whether the helmet, say, has to fit over certain critical dimensions. The dimensions would be established by constructing, by hand, a model in plaster or a similar material, conforming to the design dimensions. Here the design dimensions are those dimensions that determine the size of the model and they may be the averages of the 75th percentile or the average plus one standard deviation etc.

To construct a similar model in a computer with digital data requires some means of extracting statistical information from large quantities of data. Since computer modelling produces shapes and surfaces, this part of the problem amounts to shape averaging and this is a complex task for an object as variable as the human body. It is by no means as simple as averaging one set of numbers as a three-dimensional shape has to be built up from various dimensions that bear very little correlation to each the other.

The process is further complicated by the fact that there are no standard landmarks on the human body that act as an indisputable origin and, even if there were, the eyes, ears, noses, etc. of various subjects are at slightly different places on the body. The net effect of attempting to average different sizes of objects which are also at slightly different locations is to smear the data rather than produce an averaged shape. The problems of shape averaging have been approached by Kasvand et al. (23).

They describe a range measuring camera (also described in (22)) which delivered two-dimensional images of the elevation of the target objects above a reference plane. After this, the "pre-processing" stage was initiated. This involved taking the Z(x,y) data and extracting from it the facets of the objects in the scene, the edges and corners and their relationships to one another. This process constitutes segmenting the image. Each Z(x,y) element of data was termed a pixel and the data set was analysed in units of 3 by 3 pixels to determine gradients. From this the edges could be found.

In recognizing any object the edges constitute a particular problem as there are "ordinary edges" and "jump edges". Ordinary edges occur where one surface joined another but a "jump" edge involved a "cliff"-type edge with a discontinuous change in Z-value. It turned out that the "ordinary" edges were more difficult to detect and process than the "jump" edges.

From the 3 x 3 pixels constituting sub-sets of information from the Z(x,y) data, the surface normals were calculated. Once this information was determined, a mapping function, M, was found to transform these parameters into a new space, H, where the types of surfaces form clusters. The new space could be called "gradient space" where the axes are the gradients Zx and Zy or a "surface curvature space" where the axes are the two curvatures at any point Z(x,y), depending on which type was chosen for

the data presentation. In the gradient space, the surface normals were plotted and the plans then appeared as points, and cylinders as curves. Actually because of various inaccuracies, the data appears as "clusters" of points, particularly as the angles were quantized to discrete intervals of 5 degrees. These clusters were labelled and expanded according to the geometry they describe. Using the tilt angles of the surface normals this information was 'projected back' into the image plane. The display was cleaned by zeroing every pixel element in a 3 x 3 4-connected region that had the same label as its four neighbors. It was found that the re-created labelled image contained some spurious small regions. These were the results of certain smoothing methods and differencing techniques that resulted in any 5 x 5 pixel element or smaller not being reliable. The results of this analysis produced labelled images that were descriptions of the surfaces.

Once the image was classified, various methods were examined for obtaining object descriptions, one of which was CAD models. The model of an object was stored as a set of Pascal records corresponding to adjacent surfaces and a set of variables that related the surfaces to the model center. Taking information from the preprocessed image, a second list of records is built and elements of the same type from the scene and the model were compared. In order to identify the object, the adjacent surfaces had to be matched and the view axes and orientations all compared. All these processes involved extensive computing but they did manage to extract the information and identify the objects and their orientations correctly.

The recognition of objects and shapes, even fairly simple shapes consisting of planar sides, is not an easy job. But resolution of these types of problems are important before more complex shapes can be readily identified and manipulated.

Further work by Rioux and Boulanger reported on shape segmentation (24). In the analysis of human body shapes, there are no planes or analytical curves, so the segmentation of shape is much more complex. Segmentation is a combination of data acquisition and recognition. In order to break up a shape or set of shapes into segments, selected feature parameters have to be used. Here sine wave coding of range images was used to segment a collection of plane and cylindrical object surfaces.

The range image was first taken using a He-Ne laser scanner. These images had a range resolution of approximately 0.25 mm. The range data was stored in a 14-bit word which contained the position co-ordinates and the range data. Now a Fourier transform of a planar surface would produce a single frequency grating and the cylindrical surfaces showed up as lines in the frequency space display. The sorting, or segmentation, was done in the spectral space, by generating a mask to filter the spectrum. When image reconstruction was done, various parts of the image were selectively amplified. For example, to select the planar surfaces, certain dots were amplified.

When the image was reconstructed by means of the inverse Fourier Transform of the filtered pattern, the surface definition was good. Because 3-D images are invariant under translation and rotation, the problems of scaling (associated with position on range axis) were minimized. A presentation of two human face-forms in sine wave coding showed the ability of the technique to codify complex surfaces. The recognition, that is the matching of certain properties that define the objects, was done in the transformed space. It may be seen that this technique could be promising for the development of object recognition and other AI applications.

3.0 CONCLUSIONS

The techniques available for computing and computer-aided design in the human and bio-engineering environment are expanding rapidly. As in other fields, no one knows exactly where current developments will lead, but image processing, prosthesis fabrication in medicine, molecular modelling and "designer" drugs all show that the possibilities are only limited by the imagination. A bibliography of relevant papers is included.

4.0 REFERENCES

(1) Kroemer K.H., "Combiman - Computerized Bio-mechanical Man-Model", AMRL-TR-72-16. Wright Patterson AFB, Ohio, 1972.

(2) Popodimitrov D.K., Konstantinov V.N., Ovzovnski G.S., and Stoyanov D.I., "Dynamic Anthropometry of the Sitting Man", pp 539-547, in "Ergonomics in Machine Design", Vol. 1, Proceedings of Symposium in Prague, 2-7 October 1967, No. 14 of Occupational Safety and Health Series, Geneva, Switzerland: International Labor Office, 1969.

(3) Wartluft D.L., "Program Documentation for the Dynamic Stick-Man Program", AMRL HESS Report 71-3, Wright-Patterson Air Force Base, Ohio: Aerospace Medical Research Laboratory, 1971.

(4) Chaffin D.B., "A Computerized Biomechanical Model - Development of and Use in Studying Cross Body Actions", J. Biomechanics 2: 4, 429-441, 1969.

(5) Kilpatrick K.E., "A Model for the Design of Manual Workstations", Dissertation, Department of Industrial Engineering, Ann Arbor, Michigan: The University of Michigan, 1970.

(6) Boeing Company, (various authors) - Cockpit Geometry Evaluation - Phase II, Final Reports, Seattle, Washington: The Boeing Company, 1970.

(7) Bates F.J., Evans S.M., Krause H.E., "Three-Dimensional Display of the Combiman Model and Workspace", AMRL-TR-74-15, July 1976.

(8) Frisch G.D., O'Rourke J., "The Effectiveness of Mathematical Models as a Human Analog", SAE National Automobile Engineering and Manufacturing Meeting, Dearborn, Michigan, October 1976.

(9) Bartz J.A., Butler F.E., "A Three-Dimensional Computer Simulation of a Motor Vehicle Crash Victim", Report No. VJ-2978-V-2, Volume 1 - Volume 4, CALSPAN Corporation, Transportation Research Department, Buffalo, New York, 1972.

(10) Fleck J.T., Butler F.E., Volgel S.L., "An Improved Three-Dimensional Computer Simulation of Crash Victims", Volume 1 - Volume 4, Final Report for Contract No. DOT-FS-053-2-485, DOT Report Nos, DOT-HS-801 507 through 510, NHTSA, April 1975.

(11) Laananen D.H., "Development of a Scientific Basis for Analysis of Aircraft Seating Systems", Report No. 1510-74-36, Ultra Systems, Inc., Dynamic Science Division, Phoenix, AZ, 1974.

(12) Twigg D.W., Kames R.N., "Prometheus - A User-Oriented Program for Human Crash Dynamics", Report No. BCS40038, Boeing, Computer Services, Inc., Space and Military Applications Division, Seattle, Washington, 1974.

(13) Kames R.N., Tocher J.L., Twigg D.W., "Prometheus - A Crash Victim Simulator", Aircraft Crash Worthiness, University Press of Virginia, pp 327-346, 1975.

(14) Hendren P., Mayor P., "A Computer Graphics Approach to Investigating the Architecture of Icosahedral Viruses", Computers and Bio Medical Research 13, 581-600, 1980.

(15) Batintzsky S. et al, "Three Dimensional Computer Reconstructions of Brain Lesions from Surface Contours provided by Computed Tomography: A Prospectus", Neurosurgery 11, 1, Part 1, 1982.

(16) Ameil M., Delattre J.F., et al, "Computerized Reconstruction of an Anatomical Structure Based on Digitized Sections", Anat. Clin. 5, 261-264, 1984.

(17) Langrana N.A., Bronfeld J., "Computer-Assisted Analysis of Ligament Constraints in the Knee", Clinical Orthopedics and Related Research, 196, 42-50, June 1985.

(18) Arridge S., Moss J.P., et al, "Three Dimensional Digitization of the Face and Skull", J. max-fac. Surg. 13, 136-143, 1985.

(19) Dore S., Bobyn J., "Unique Orthopedic Implants", SOMA, 44-53, April, 1986.

(20) Walker P., Rovick J., et al, "Computer Graphics looks at the Knee: Motion Monitoring to the Total Artificial Joint", SOMA, 6-13, July, 1986.

(21) Movie,BYU: Christiansen H.N., Department of Computer Graphics, Brigham Young University, Provo, Utah (Calspan Model).

(22) Boulanger P., Rioux R., Evans K., Ruhlmann L., "Interface between a 3-D Laser Scanner and a CAD/CAM System", NRC Report NRCC 27454, Advances in CAD/CAM and Robotics: NRC contributions, May 1987.

(23) Kasvand T., Oka R., et al, "Segmentation, Learning, and Recognition of Objects in Range Camera Images", Advances in CAD/CAM and Robotics, NRCC No. 27454, ERB-1003, pp 390-400, May, 1987.

(24) Rioux M., Boulanger P., et al, "Segmentation of Range Images Using sine Wave coding and Fourier Transformation", Advances in CAD/CAM and Robotics, NRCC, No. 27454, ERB-1003, pp 414-420, May 1987.

5.0 BIBLIOGRAPHY

"A Directory of Computer Software Applications - Bio Medical Technology and Human Factors, 1970-1979", NTIS-SA-79-04, PB-292-724-2 7900, March 1979.

Aphin J.E., "The Application of Anthropometric Survey Data to Aircrew Clothing Sizing", Royal Aircraft Establishment Farnborough, AD-A150545, RAE-TR-84050, May 1984.

Askren W.B., Campbell W.B., et al, "Feasibility of a Computer Simulation Method for Evaluating Human Effects on Nuclear Systems Safety", Air Force Human Resources Laboratory, Brooks AFB TX, AFHRL-TR-76-18, AD-A025 310, May 1976.

Baughman L.D., "The Development of an Interactive Computer Program to Produce Body Description Data", UDR-TR-83-06, University of Dayton, Ohio, Research Institute.

Bartholomew J.C., "The Effects of Multiple Anthropometric Constraints on the Accommodation of Personnel in Operational Naval Aircraft", Naval Postgraduate School, Monterey, CA, September, 1980.

Bensel C.K., "Proceedings of the Human Factors Society 23rd Annual Meeting, Boston, Mass., 1979. Army Natick Research and Development Command, Natick, Mass. Human Factors Group and Human Factors Society, Santa Monica, CA., 1979.

Bittner A.C., "Computerized Accommodated Percentage Evaluation (CAPE) Model for Cockpit Analysis and other Exclusion Studies", Pacific Missile Test Center, Point Mugn, CA, PMTC-TP-75-49, Dec. 1975.

Brandt W., Wartluft D.L., Sebasky G.M., "Summary of Several Software Packages Developed for Human Engineering Systems Simulation (HESS) Facility", F33615-69-C-1901, F33615-70-C-1312, AD-731-581, 7100, September 1971.

Collins S.H., Lehan T.J., et al, "Development of Software Tools for Intervisibility Analysis, Using the DCIEM Spatial Database Management System", Defence and Civil Institute of Environmental Medicine, 406986, 1985.

Dariet P., Gardenet P., et al, "Voludensitometry, Three-Dimensional Display of Medical Objects", CEA-CONF-7285, DE 85750678-XAB 8508, May 1984.

Evans S., Beer B.D., "A Human Engineering Evaluation of Visibility from the DDH280 Bridge", Defence and Civil Institute of Environmental Medicine, Downsview, Ont., DCIEM-85-R-01, Jan. 1985.

Hendy K.C., Anderson K.W., "A Graphic Anthropometric Aid for Seating and Workplace Design", Aeronautical Research Laboratory, Melbourne, Australia, ARL-SYS-29, AR-003-023, April 1984.

Hidson D.J., "Computer-Aided Design of a Respirator Facepiece Model", DREO Report DREO-902, Defence Research Establishment Ottawa, December 1984.

Hockstra P.N., "ADAPS -Anthropometric Design Assessment Program System - WOM84: Anthropometric Model of the Dutch Woman", PB86-146974-XAB 8605, July, 1985.

Hockstra P.N., "ADAPS - Anthropometric Design Assessment Program System - MAN84: Anthropometric Model of the Dutch Man", PB86-146842-XAB 8605, July 1985.

Jacob, R.J., Egeth H.E., Beran W., "The Face as a Data Display", N00014-67-A-0163-0012, AD-A013-352-0, 7500, July 1975.

Jermain W., "Computer-Modelling of the Body-Head-Helmet System, Volume 1", DABT01-74-C-0231, AD-A023-785-9, 7600, February 1976.

Ketcham-Weidl M.A., Bittner A.C., "Anthropometric Accommodation of a Female Population in a Workplace Designed to Male Standards", Pacific Missile Test Center, Point Mugn, CA, PMTC-TP-76-3, AD-B022 540L, December, 1976.

Knapp J.G., "Computer Graphics Representation of Mandibular Movements in Three Dimensions: The Method", Journal of Oral Rehabilitation, 1983, 10, 295-305.

Komhauser M., "Biodynamic Modelling and Scaling: Anthropometric Dummies, Animals and Man, "AMRL-TR-71-29-PAPER-6, AD-740-443, 7200, December 1971.

Krumme H., Guenay M., Nagel H., Delling G., "Computerized Simulation of Bone Remodelling: Graphic Demonstration of Dynamic Processes", Metab. Bone Dis. & Rel. Res., 5, 253-257, 1984.

Lins W.F., "Human Vibration Response Measurement", Army Tank - Automative Command, Warren, MI, USA, TACOM-11551, AD-901 195L, June 1972.

McCann C., "Graphic Display Interaction - Part I: Literature Review", Defence and Civil Institute of Environmental Medicine, Downsview, Ontario. DCIEM-TR-78-X-4, AD-A055 402, January 1978.

McCann C., "Graphic Display Interaction - Part II: Information Structure and Basic Functions", DCIEM-TR-78-X-5, Defence and Civil Institute of Environmental Medicine, AD-A055 403, January 1978.

Planchard J.A., Perkins T.M., "Weapon System Effectiveness Analysis, Opitimization and Simulation - Phase I, Volume III, Development of a Human Operator Model for a Tracking Task", Air Force Armament Laboratory, Eglin AFB, FL, AFATL-TR-71-20-Vol-3, AD-907 444, February 1971.

Porteous E.M., "An Appraisal of Computer Aids for Human Engineering Design", Admiralty Marine Technology Establishment, Teddington, UK, AMT(E)-TM-80103, BR-75950, March 1980.

Pulat Babur Mustafa, "Computer-Aided Techniques for Crew Station Design...", N00014-81-C-0320, AD-A132-981-2 8400, June 1983.

Ramsey H.R., Atwood M.E., "A Critically Annotated Bibliography of the Literature on Human Factors in Computer Systems", Science Applications Inc., Englewood, CO, USA. SAI-78-070-DEN, May 1978.

Ramsey H.R., Atwood M.E., "Human Factors in Computer Systems: A Review of the Literature", Science Applications Inc., Englewood, CO, USA. SAI-79-111-DEN, September 1979.

Reyholds H.M., "A Foundation for Systems Anthropometry, Phase I", Michigin University, UM-HSRI-77-7.

Robinette K., Churchill T., "Design Criteria for Characterizing Individuals in the Extreme Upper and Lower Body Size Ranges"

Rothwell P.L., Beevis D., "The Approach to Aircrew Anthropometry and Crew Station Size Limitations in the Canadian Forces", DCIEM, Downsview, Ontario, DCIEM-85-C-40, October, 1985.

Rothwell P.L., "Use of Man-Modelling CAD Systems by the Ergonomist", July, 1985, Defence and Civil Institute of Environmental Medicine No. 85-R-26.

Rothwell P.L., "Selection of a Man-Modelling CAD Program to Assess the Physical Compatibility Between Aircrew and Aircraft", DCIEM-85-C-36, Defence and Civil Institute of Environmental Medicine, 1985.

Sampson P.D., "Dental Arch Shape: A Statistical Analysis Using Comic Sections", Am. J. Orthod., May, 79 (5), 535-548, 1981.

Siegel A.I., "Computer Simulation of Human Performance in Electronic Processed Imagery Systems", Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, USA, AMRL-TR-79-117, Jan., 1981.

Spray D.F., "Functional Requirements for a Computer Graphics Model of a Maintenance Technician", AFIT-LSSR-63-83, AD-A134-385-4, 8400, School of Systems and Logistics, Air Force Institute of Technology, Wright Patterson Air Force Base, OH, September 1983.

Tanner P., "Action: A Graphics Aid to Interacting with Models and Simulations", National Research Council of Canada, Radio and Electrical Engineering Division (REED), NRC/REED-ERB-920, December, 1979.

USACDCEC 037210, "Computer-Aided Terrain Mobility Analysis Technique (CATMAT) Test", Army Combat Developments Experimentation Command, Ford Ord., CA, September, 1977, AD-B021-538L.

Zaytsev I.A., Raksha A.A., "Computerized Design of Motor Vehicle Bodies", Army Foreign Science and Technology Center, Charlottesville, VA. FSTC-HT-853-80, AD-B054 044L, September 1980.

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(highest classification of Title, Abstract, Keywords)

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(Security classification of title, body of abstract and indexing annotation must be entered when the overall document is classified)

1. ORIGINATOR (the name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Establishment sponsoring a contractor's report, or tasking agency, are entered in section 8.) DEFENCE RESEARCH ESTABLISHMENT OTTAWA Department of National Defence Ottawa, Ontario K1A 0Z4	2. SECURITY CLASSIFICATION (overall security classification of the document, including special warning terms if applicable) UNCLASSIFIED

3. TITLE (the complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S,C,R or U) in parentheses after the title.)

'COMPUTER-AIDED DESIGN AND BIO-ENGINEERING: A REVIEW OF THE LITERATURE' (U)

4. AUTHORS (Last name, first name, middle initial)

HIDSON, David J.

5. DATE OF PUBLICATION (month and year of publication of document) JULY 1988	6a. NO. OF PAGES (total containing information. Include Annexes, Appendices, etc.) 26	6b. NO. OF REFS (total cited in document) 24

7. DESCRIPTIVE NOTES (the category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

TECHNICAL NOTE

8. SPONSORING ACTIVITY (the name of the department project office or laboratory sponsoring the research and development. Include the address.)

9a. PROJECT OR GRANT NO. (if appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant) 051LD	9b. CONTRACT NO. (if appropriate, the applicable number under which the document was written)
10a. ORIGINATOR'S DOCUMENT NUMBER (the official document number by which the document is identified by the originating activity. This number must be unique to this document.) DREO TECHNICAL NOTE NO. 88- 31	10b. OTHER DOCUMENT NOS. (Any other numbers which may be assigned this document either by the originator or by the sponsor)

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